

RECENT RESEARCH RESULTS IN WET GAS FLOW

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1 INTRODUCTION

Wet gas metering is being used increasingly in economically marginal fields, reducing the capital costs by allowing several small fields to share common platform infrastructure. The development of reliable wet gas meters is a key requirement in the oil and gas industry at present. Such meters should be able to measure both the gas and liquid flowrates if desired. However, in some cases the liquid flowrate is not important, requiring only the gas flowrate to be measured accurately.

If the liquid flowrate is low and/or reasonably steady, and can be determined by other means, i.e. tracer technique or periodic sampling, then a standard single phase gas meter, whose response to the presence of liquid is known, can be used with a correction applied to the reading to account for the liquid.

In some other situations, unexpected well conditions can result in a higher liquid loading in the gas stream causing nominally dry gas meters to be exposed to liquids. This can happen on inappropriately sized separator systems that are not tolerant of liquid slugs. In this case it is important for the operator to be able to establish the error in gas measurement, particularly if the meter is used for allocation purposes.

This paper analyses the performance of a vortex meter in such wet gas conditions. Test data taken at NEL, during the 1999-2002 DTI Flow Programme, Project No. FDMU07, is analysed for general performance and limits of operability. The results are compared with the small amount of previous data available.

It is understood that some of these meter types may not always be intentionally applied in a wet gas situation, however, it is important to know how they are affected by the presence of liquid in case they are subjected to wet gas flow unexpectedly.

2 METER OPERATING PRINCIPLES

A Vortex meter operates by placing a bluff body (often triangular, but can be circular) into a flow that generates a stream of vortices off its leading edges. The frequency of the production of these vortices is linearly related to the fluid velocity. Sensors downstream of the bluff body are used to measure the vortex frequency and consequently the velocity and flowrate. The type of sensor can vary, with optical or pressure sensors often used.

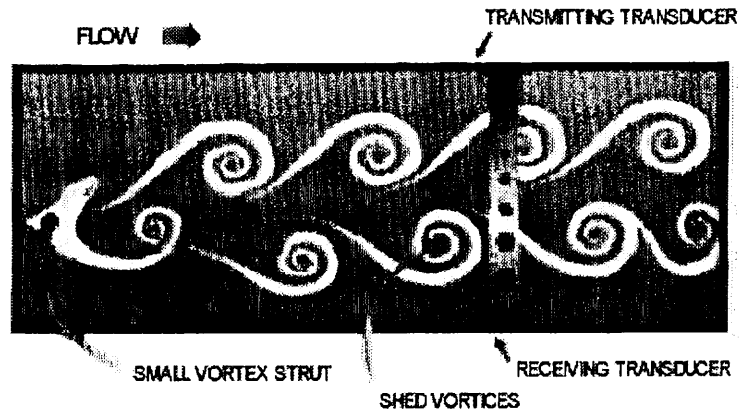


Fig. 1. Illustration of vortex shedding principle.

Given that the vortex meter is a velocity measuring device, it was expected that in wet gas this meter would be affected by the blockage factor introduced by the liquid, in that the liquid presence leaves less flow area for the gas, which therefore flows faster causing the meter to over-read the gas flowrate. The expected influence of the liquid on the vortex generation was unclear, but it was thought that the higher the liquid content the more likely it would be to disrupt the vortex generation. In the tests at NEL a 4-inch Fisher-Rosemount 8800A Vortex meter was used.

3 NEL WET GAS TEST FACILITY

The NEL tests were conducted on NEL's high pressure wet gas test facility, described in detail elsewhere [1]. This facility can operate at pressures up to 60 bar, with gas flowrates up to 1000 m³/hr in wet gas mode, and liquid volume fractions up to 5%, with higher fractions achievable at low gas flowrates. The facility uses nitrogen for the gas phase and a kerosene substitute for the liquid phase. These have been selected to provide a balance between representative test fluids and high accuracy, traceable reference metering. There is no phase transfer between the fluids and therefore complicated PVT models are not required to determine the reference flowrates of each phase at the test meter.

The NEL Wet Gas Facility can be used to test meters across a wide range of operating conditions. Meters can be installed in horizontal, vertical or even inclined test sections to investigate the effect of pipeline orientation or to simulate a client's particular installation set-up.

4 METER PERFORMANCE

4.1 Test Conditions

The vortex meter was tested in a horizontal orientation, with the vortex shedding bar in a horizontal position across the middle of the pipe. This set-up was designed to minimize the impact of the liquid on the vortex generation. The meter was tested initially in dry gas to determine baseline performance, and then in wet gas.

The meter was tested across a range of gas and liquid flowrates to investigate the effect of liquid content and superficial gas velocity on the meter performance. The gas velocity ranged from 3 m/s up to 30 m/s, with liquid volume fractions of 0.1%, 0.25%, 0.5%, 1%, 2.5% and 5%, where achievable. The tests were conducted at three test pressures, 15 bar, 30 bar and 60 bar, allowing the influence of the gas density on the meter performance to be investigated.

The overall test envelope is shown in Table 1, expressed by the superficial gas velocity (SGV), corresponding gas Froude number, Fr_g , and maximum achieved Lockhart-Martinelli (X) value. The Froude number and Lockhart-Martinelli parameters are defined as:

$$Fr_g = \frac{v_{sg}}{\sqrt{gD}} \sqrt{\frac{\rho_g}{\rho_l - \rho_g}} \quad \text{and} \quad X = \frac{m_l}{m_g} \sqrt{\frac{\rho_g}{\rho_l}}$$

where v_{sg} = superficial gas velocity [m/s]
 g = gravitational constant [m^2/s]
 D = pipe internal diameter [m]
 ρ = density (subscript l for liquid, g for gas) [kg/m^3]
 m = mass flowrate (subscript l for liquid, g for gas) [kg/s]

Table 1. Test envelope for Vortex meter tests

Pressure (barg)	SGV (m/s)	Fr_g (-)	Max X (-)	Pressure (barg)	SGV (m/s)	Fr_g (-)	Max X (-)	Pressure (barg)	SGV (m/s)	Fr_g (-)	Max X (-)
	3	0.47	0.163		3	0.67	0.244		3	0.95	0.174
	5	0.77	0.346		5	1.09	0.243		5	1.53	0.180
	10	1.54	0.341		10	2.2	0.244		10	3.13	0.178
15	15	2.32	0.168	30	15	3.3	0.120	60	15	4.67	0.180
	20	3.09	0.065		20	4.4	0.047		20	6.3	0.085
	25	3.87	0.031		25	5.6	0.146		25	7.9	0.033
	30	4.69	0.033		30	6.7	0.024		30	9.5	0.033

The superficial gas velocities used in these tests were chosen to produce a range of flow patterns in the test line. These flow patterns ranged from wavy-stratified, through a transitional zone and into an annular-mist region. However, the static pressure in the line also influences the flow pattern, tending to shift it toward an annular-mist regime as pressure increases. In wavy-stratified flow conditions the liquid runs along the bottom of the pipe. The surface of the liquid is however quite turbulent with the presence of waves as well as an indistinct, mixed two-phase interface. The slip between gas and liquid in this regime is quite high, with the gas generally travelling much faster than the liquid.

As the gas velocity increases, the flow pattern changes into a transitional form, with some liquid moving along the pipe bottom, some starting to spread out around the pipe wall and some being picked-up as droplets moving with the gas. At high gas velocities a large fraction of the liquid is suspended in the gas flow, with a continuous interchange between a liquid film at the wall and the gas core.

4.2 Test Results

The combined dry and wet gas results for the 15 bar tests are shown in Fig. 4. The data is presented in terms of meter error (relative to gas reference flowrate) against superficial gas velocity, with the data ordered by liquid volume fraction (and corresponding Lockhart-Martinelli parameter). There are some interesting patterns in the data. It can be seen first of all that the dry gas performance of the meter is good, within 1% across the velocity range tested.

Once even the smallest amount of liquid, 0.1% by volume, is added to the gas flow, there is an increase in the meter error, i.e. the meter is measuring more gas than really exists. However, it is clear that the meter error is relatively flat with respect to the superficial gas velocity, varying between approximately 0.5% and 2% error.

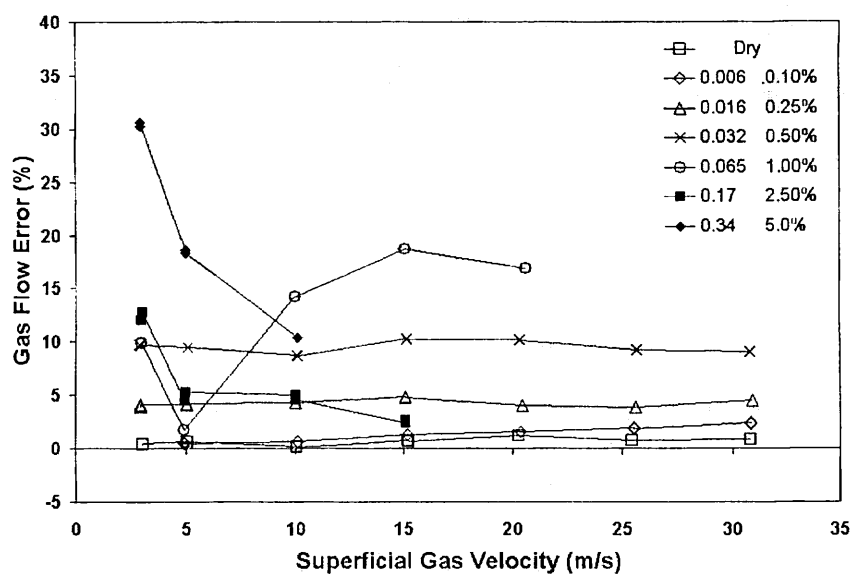


Fig. 4. Vortex meter wet gas results at 15 bar (ordered by X and LVF)

As the liquid volume fraction increases to 0.25% and then 0.5%, the meter error increases further. It is clear again that the meter error is flat with respect to superficial gas velocity. The absolute value of the error is also interesting in that when the liquid volume fraction is doubled from 0.25% to 0.5%, the meter error is close to doubled, from just under 5% to approximately 10%.

These trends, however, do not continue as the liquid volume fraction is increased to 1%, 2.5% and 5%. At the lowest gas velocity the meter error does increase, however when the velocity increases to 5 m/s the meter error drops significantly. At higher again gas velocities the meter error increases again at 1% LVF, remains relatively flat at 2.5% LVF and drops further at 5% LVF. The exact explanation for this behaviour is unknown, however it would appear that at certain combinations of gas velocity and liquid volume fraction the generation and/or detection of vortices is being affected, resulting in a reduction in meter flowrate output.

Most of the inconsistent behaviour occurs at the lower test velocities, where it is likely that a transitional flow pattern exists, even at 15 barg. Unfortunately it was not possible to test the meter at high SGVs and LVFs together, so it is not possible to determine if the errors would return to a stable level. However, some further repeat

test runs conducted at the 'unstable' vortex-meter test points at 15 barg in fact produced almost the same error values as the original test runs, indicating a consistent behaviour in the meter performance.

The combined dry and wet gas results for the 30 bar tests are shown in Fig. 5, presented in the same manner as the 15 bar data. Again there are some interesting results to be seen in this data. As at 15 bar, the dry gas performance of the meter is good, mostly within 1% across the range tested.

When liquid is introduced into the gas stream the meter error increases, as at 15 bar. Although at 30 bar there is a bit more scatter between the lower LVF data sets, in general the meter error increases with increasing liquid fraction. At the highest liquid fractions tested at 30 bar, 2.5% and 5%, the erratic behaviour observed at 15 bar can still be seen, with the meter error varying over a significant range. Again, it is believed to be caused by liquid interfering with the vortex generation and/or detection.

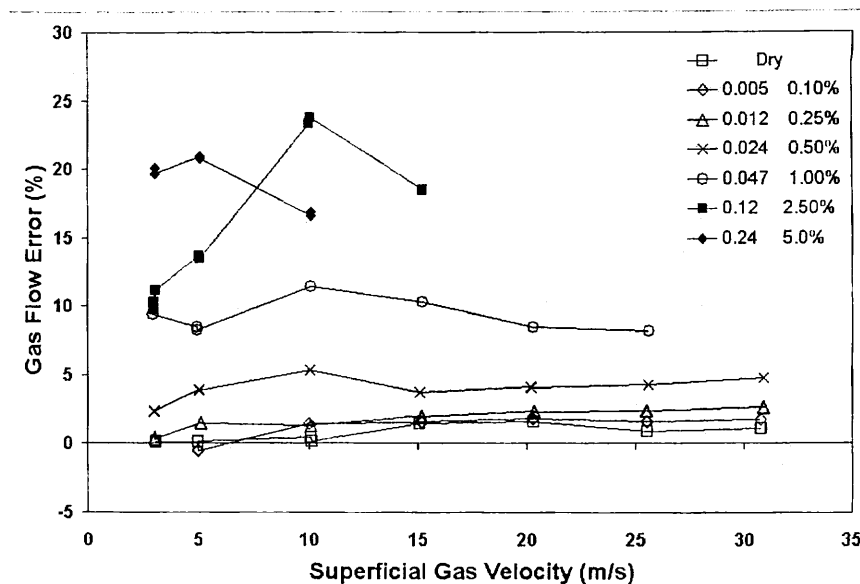


Fig. 5. Vortex meter wet gas results at 30 bar (ordered by X and LVF)

One of the most significant differences with the 30 bar results is that the meter error stays relatively flat until 1% LVF, as opposed to only 0.5% LVF at 15 bar. Another significant aspect is that the absolute value of the meter error is lower than at 15 bar. For example at 15 bar the meter error at 0.5% LVF was approximately 10%, whereas at 30 bar it was approximately 4% to 5%.

It is thought that these two effects are caused by the fact that at a higher pressure and correspondingly higher gas density, the liquid hold-up (i.e. fraction of pipe area occupied by liquid) is lower due to the increased momentum and "push" of the gas carrying the liquid through the pipe more effectively. This leads to a smaller blockage effect and consequently a lower meter error and less interference in the vortex generation for any given liquid volume fraction.

Finally, the combined dry and wet gas results for the 60 bar tests are shown in Fig. 6, again presented in the same manner as the 15 bar and 30 bar data. Again some of the same trends and factors can be seen in this data. As at both lower pressures, the dry gas performance of the meter is good, mostly within 1% across the range tested.

At 60 bar, when liquid is introduced into the gas stream the meter error increases, as at 15 bar and 30 bar. As at 30 bar there is some scatter and overlap between the lower LVF data sets at 60 bar, however, in general, the meter error increases with increasing liquid fraction. At the highest liquid fractions tested at 60 bar, 2.5% and 5%, the erratic behaviour observed at 15 bar and 30 bar can still be seen, although to a much lesser degree, with the meter error varying over a smaller range. Once again, it is believed to be caused by liquid interfering with the vortex generation and/or detection.

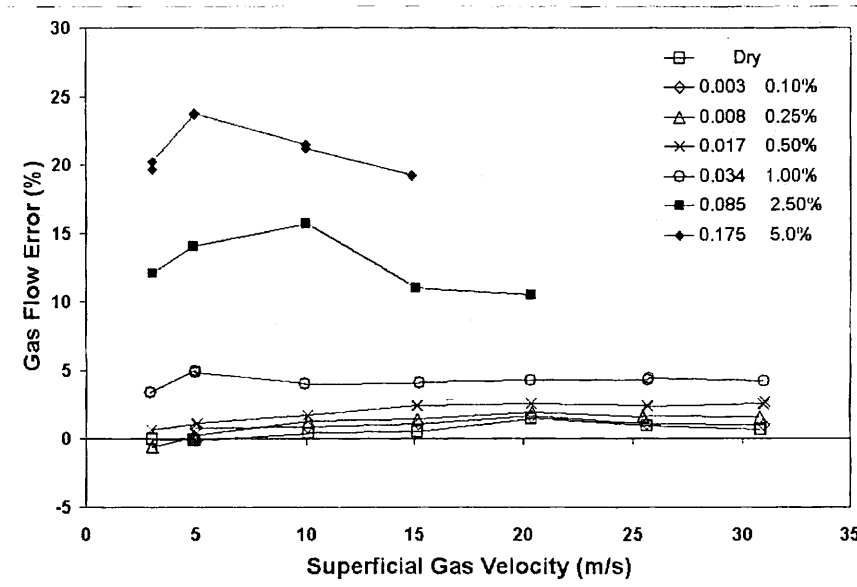


Fig. 6. Vortex meter wet gas results at 60 bar (ordered by X and LVF)

As with the 30 bar data, the most significant differences with the 60 bar results are that the meter error stays flatter until higher LVFs, and that the absolute magnitude of the meter error is even lower again. For example at 15 bar the meter error at 1% LVF was approximately 10% at 30 bar, whereas at 60 bar it was approximately 4% to 5%.

Again it is thought that these two effects are caused by the fact that at higher pressures and correspondingly higher gas densities, the liquid hold-up is lower, leading to a smaller blockage effect and consequently a lower meter error and less interference in the vortex generation for any given liquid volume fraction.

4.3 Comparison with Previous Work

In their 1989 paper [2] Nederveen et al describe some (rare) vortex meter wet gas test results, obtained as part of a wider test programme investigating wet gas flow measurement under actual field and laboratory conditions for NAM in the Netherlands. The vortex meter used had a nominal diameter of 75mm and tests were conducted at 80 bar and at two gas flowrates: 85,000 and 135,000 Nm³/day. These correspond to superficial gas velocities of approximately 2.9 and 4.6 m/s respectively and gas Froude numbers of 0.81 and 1.29 respectively.

These values put the tests in the region of the transitional boundary between stratified-wavy and annular-mist flow regimes. Water was injected into the natural gas flow line downstream of a reference Venturi meter and upstream of the vortex

meter. Liquid contents (LGR=Liquid/Gas Mass Ratio) ranged from 0 to 300 m³ liquid/10⁶ Nm³ gas (20 l/min maximum injected flowrate). This equates to a maximum liquid volume fraction of 2.56% at the minimum gas flowrate and 1.63% at the maximum gas flowrate.

The results of their tests are reproduced in Fig. 7 below. An increasing liquid content (at both gas flowrates) clearly increases the meter over-reading relative to the dry gas values, with a maximum shift in the meter reading of around 14% at the maximum SGV and LGR tested. The authors concluded that the meter over-reading was dependent mainly on the liquid flowrate, and that the magnitude of the change in the meter error depends on the slip rate between the gas and liquid phases. The authors also suggested that vortex meters were not suitable for measuring gas flows containing entrained liquids due to an inability to produce predictable readings.

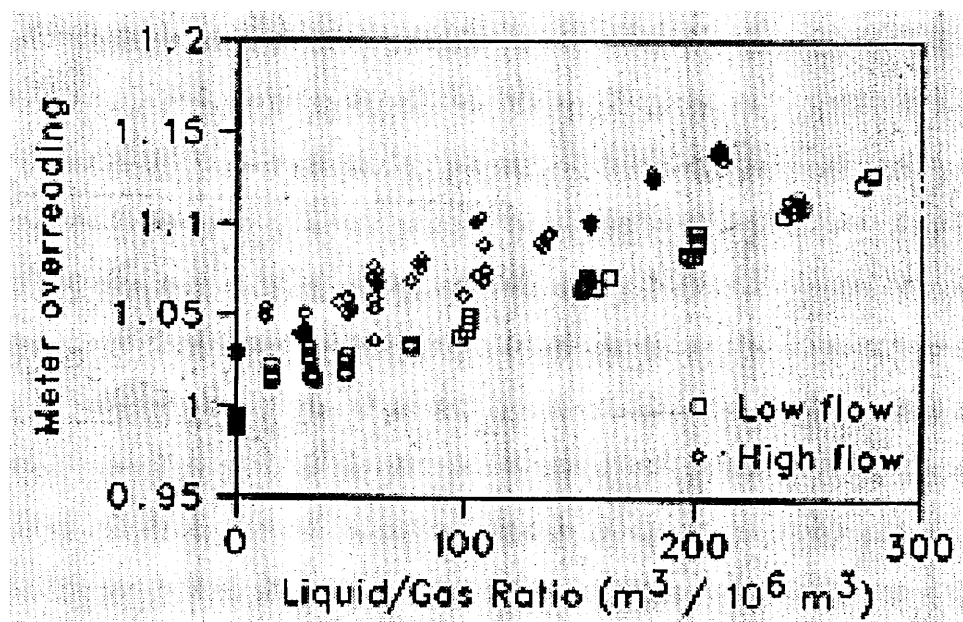


Fig. 7. Reproduction of results from Ref. [3].

The NEL results at 60bar (closest pressure to Ref. [3]) are presented in Fig. 8 below in a similar manner.

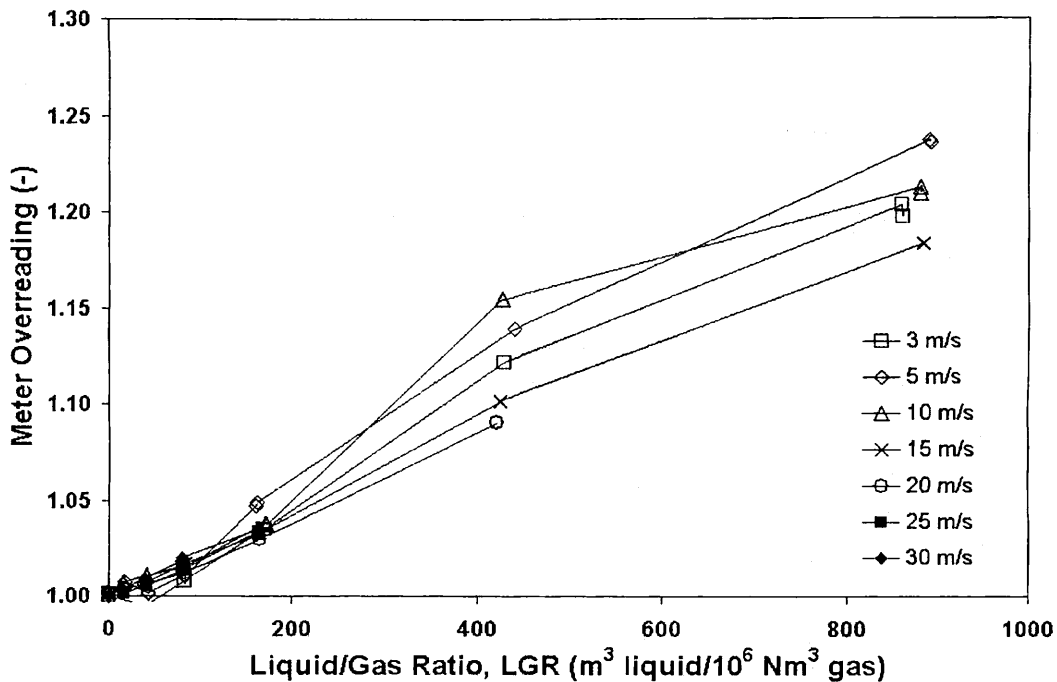


Fig. 8. NEL over-reading as a function of the LGR and SGV at 60 bar

The NEL results tend to agree qualitatively with the previously published data, however the absolute over-reading values are much lower for the NEL data at a given LGR. For example, at an LGR of 200 m³ liquid/10⁶ Nm³ gas, the data of Nederveen et al suggest a meter over-reading range of between 9% and 14%. At the same LGR for the NEL data a meter over-reading of around 5% is produced - a significant difference.

The larger slope of the over-reading curves of Nederveen et al may be due to a higher relative holdup of liquid in the test line. Nederveen et al did use water as the liquid phase in their tests, while at NEL a kerosene substitute was used. This results in a difference in liquid density of nearly 20%, which even at the higher test pressure of Nederveen et al appears likely to produce a difference in liquid holdup, however it would be unlikely to cause the difference in over-reading seen here.

Another point to note with respect to Fig. 7 is the separation in the over-readings at the two test gas flowrates used. At first glance it appears as if there is a gas flowrate effect. This is even stated by the authors. However, closer inspection of Fig. 7 shows that some dry gas points (ie LGR = 0) have been included. At the low gas test flowrate the over-reading is in fact slightly less than 1, while at the higher flowrate it is closer to 1.03 (a 3% shift). If the wet gas data were calculated relative to these dry gas values, then both data sets would collapse directly onto each other and it could be concluded that the gas flowrates used had no effect on the meter performance. This would then agree with the findings of the NEL tests. For more detailed comparison with previous data, the reader is directed to Ref. [1].

4.4 Determination of Correction Factors From NEL Data

As discussed in the introduction, if it is only the gas measurement that is important in a wet gas application, then the possibility exists to use a single phase meter, such as the vortex meter, as long as some form of correction factor is available to account for the effect that the liquid has on the measurement. To develop any correction factor it is important to be able to represent the data in suitable manner.

When the NEL data is presented as in Fig. 8, the trend in the data becomes clearer with respect to meter error against liquid content. Figs. 9, 10 and 11 below show the NEL data plotted in terms of meter error against Lockhart-Martinelli value, at 15 bar, 30 bar and 60 bar respectively.

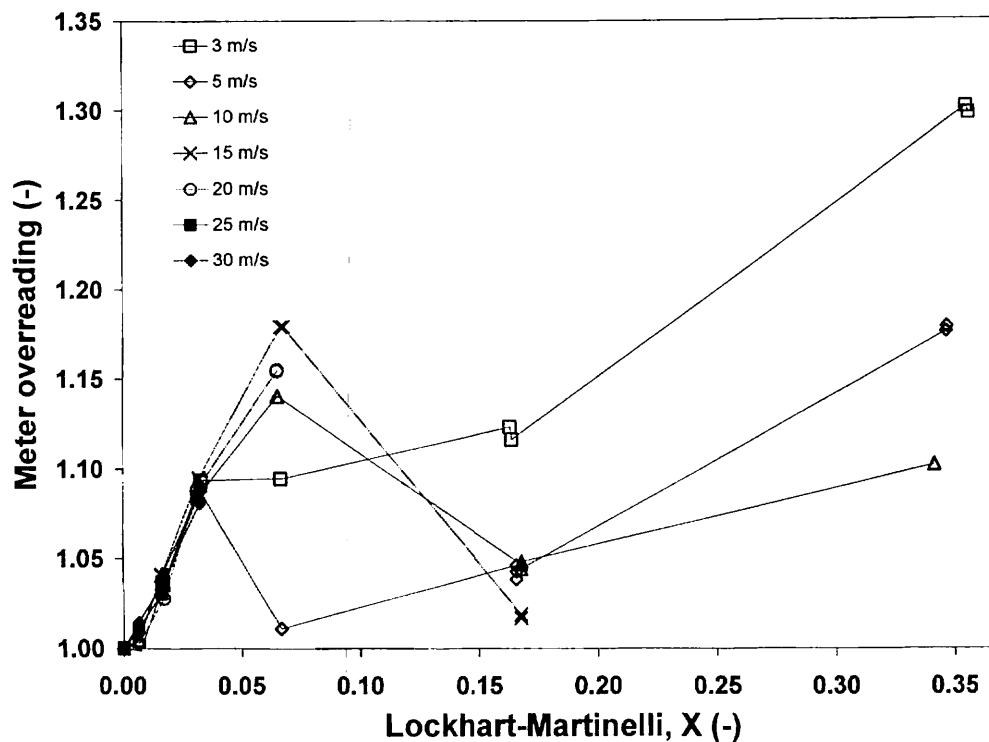


Fig. 9. NEL vortex meter data at 15 bar against X.

It is clear from Figs. 9, 10 and 11 that, as discussed in section 4.2, there are clearly identifiable limits of stable operation for this meter at each different pressure. At 15 bar, the meter appears to be reasonably stable and have a predictable error up to Lockhart-Martinelli values of 0.03, which corresponds to a liquid volume fraction of 0.5%. At 30 bar this limit increases to approximately $X = 0.05$, or $LVF = 1\%$, and at 60 bar the limit is significantly higher, with $X = 0.18$, or $LVF = 5.0\%$. Above these respective limits at each pressure the meter error appears unstable and could not be predicted with any degree of confidence.

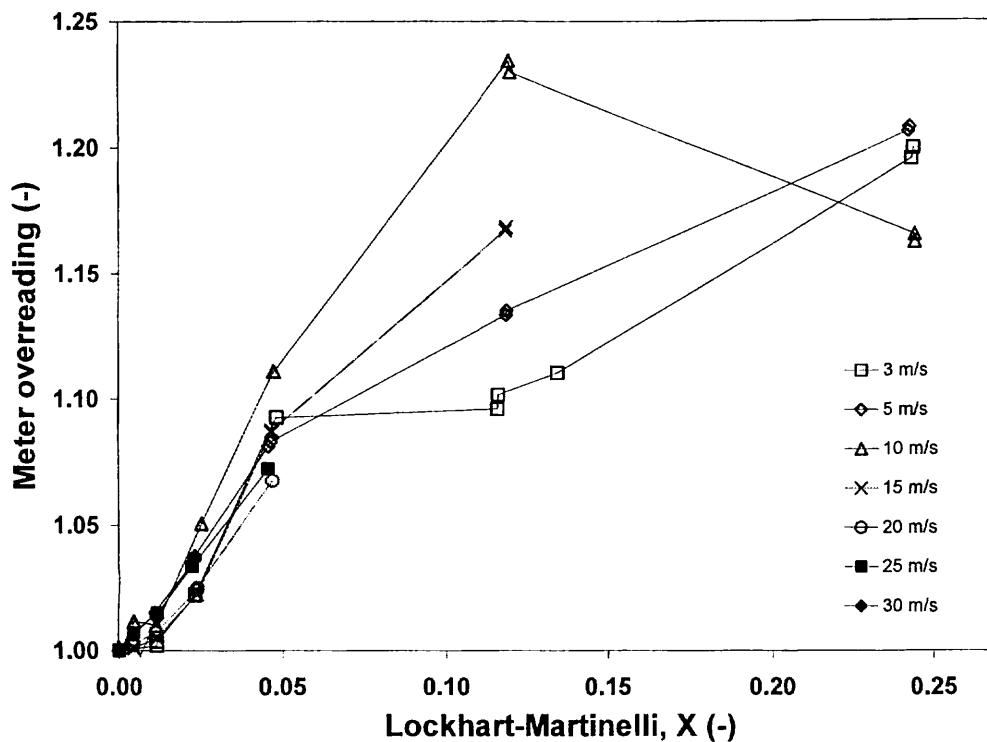


Fig. 10. NEL vortex meter data at 30 bar against X.

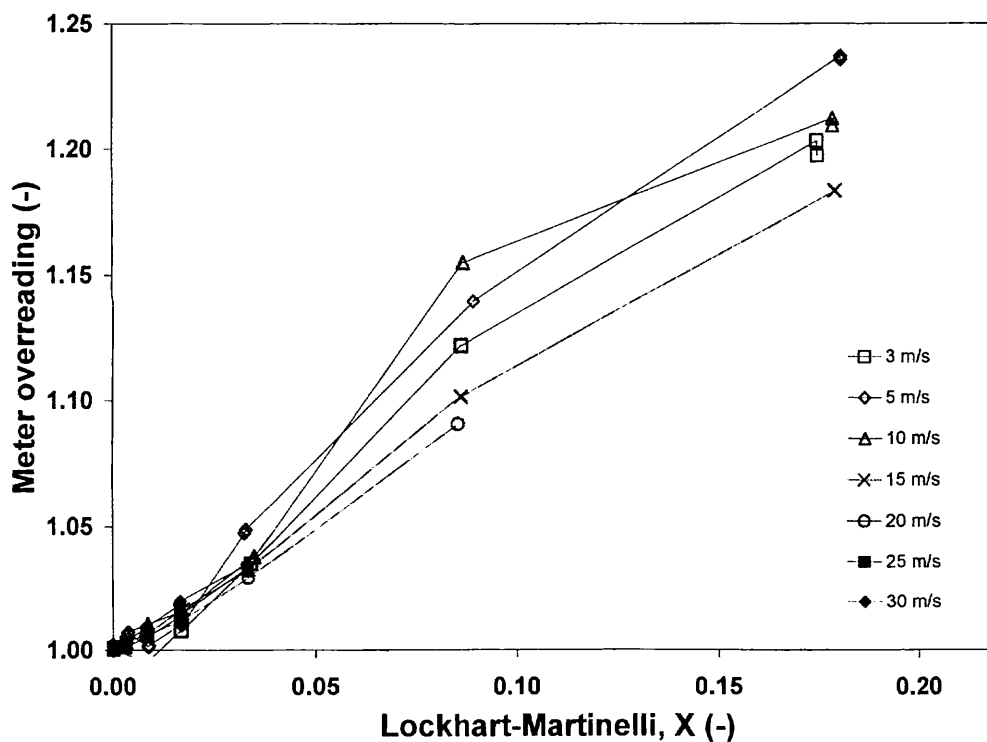


Fig. 11. NEL vortex meter data at 60 bar against X.

However, if the data within the limits prescribed above is analysed more closely, then even though there is still some variation within the data for any given liquid fraction, as a result of the different superficial gas velocities tested, it is possible to consider an average fit to the data for the purposes of generating a correction factor to account for the liquid induced error. Fig. 12 show this approach, with linear best fit curves fitted to the 15 bar, 30 bar and 60 bar data only within the limits discussed.

When these correction factors are subsequently applied to the raw test data the corrected flowrates can be calculated for each pressure. These results are shown in Fig. 13 for each of the three pressures. It can be seen than once corrected, most points lie within a +/- 2% error band when compared with the reference flow, and all are within 5%.

It must be stressed however, that this is merely an illustration of one particular case and that the limits of operation and correction factors are very unlikely to be generally applicable to other vortex meters. Substantial further testing would be required to attempt to produce a general solution. If this approach was desired for any given meter, then specific testing would be recommended on that meter at the appropriate conditions.

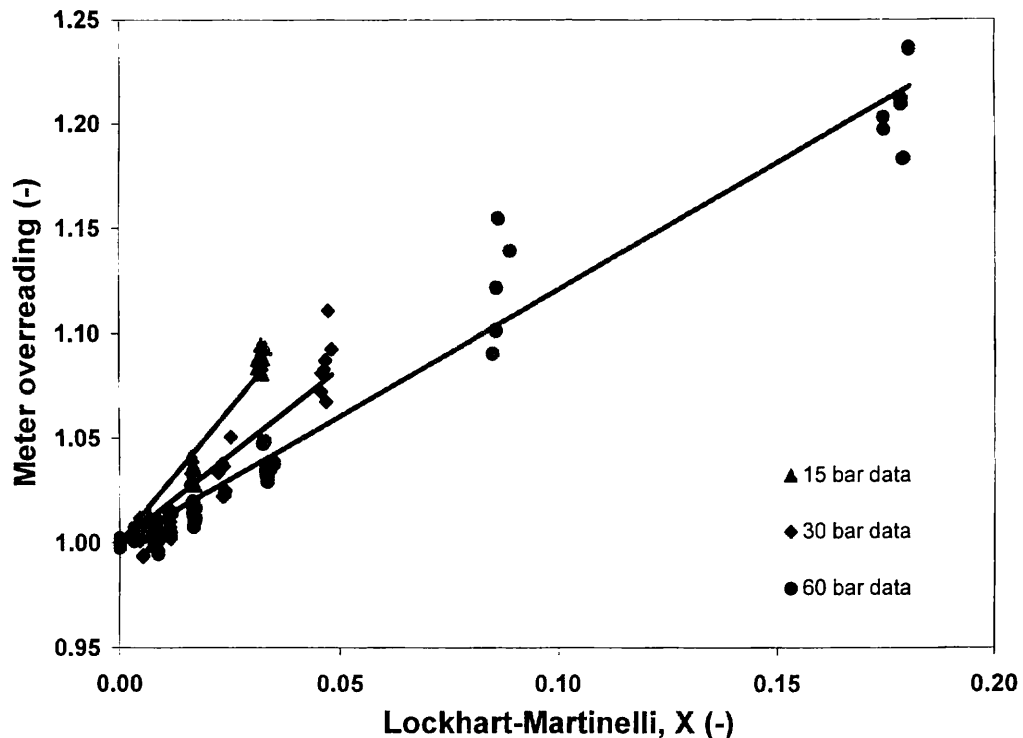
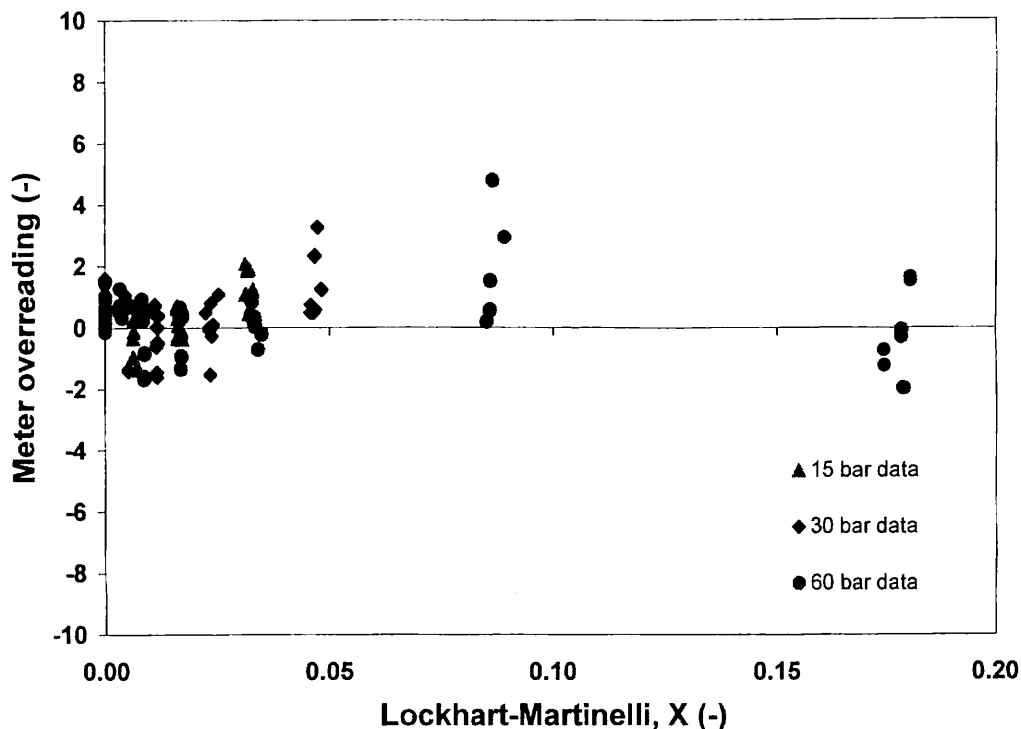


Fig. 12. NEL vortex meter data within "stable error" limits



6 REFERENCES

- [1] NEL Report 2002-100.
- [2] Nederveen, N., Washington, G.V. and Batstra, F.H., "Wet Gas Flow Measurement", SPE 19077, Presented at the SPE Gas Technology Symposium, Dallas, Texas, June 7-9, 1989.